

Towards a Decision Support System for Space Flight Operations

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Abstract

The Mission Operations Directorate (MOD) at the Johnson Space Center (JSC) has put in place a Model Based Systems Engineering (MBSE) technological framework for the development and execution of the Flight Production Process (FPP). This framework has provided much added value and return on investment to date. This paper describes a vision for a model based Decision Support System (DSS) for the development and execution of the FPP and its design and development process. The envisioned system extends the existing MBSE methodology and technological framework which is currently in use.

The MBSE technological framework currently in place enables the systematic collection and integration of data required for building an FPP model for a diverse set of missions. This framework includes the technology, people and processes required for rapid development of architectural artifacts. It is used to build a feasible FPP model for the first flight of spacecraft and for recurrent flights throughout the life of the program. This model greatly enhances our ability to effectively engage with a new customer. It provides a preliminary work breakdown structure, data flow information and a master schedule based on its existing knowledge base. These artifacts are then refined and iterated upon with the customer for the development of a robust end-to-end, high-level integrated master schedule and its associated dependencies.

The vision is to enhance this framework to enable its application for uncertainty management, decision support and optimization of the design and execution of the FPP by the program. Furthermore, this enhanced framework will enable the agile response and redesign of the FPP based on observed system behavior. The discrepancy of the anticipated system behavior and the observed behavior may be due to the processing of tasks internally, or due to external factors such as changes in program requirements or conditions associated with other organizations that are outside of MOD. The paper provides a roadmap for the three increments of this vision. These increments include (1) hardware and software system components and interfaces with the NASA ground system, (2) uncertainty management and (3) re-planning and automated

execution. Each of these increments provides value independently; but some may also enable building of a subsequent increment.

1. First Increment: Background

A language for the capture, representation and storage of architecture and design information for the FPP has been developed, established and is currently in use. This language is the basis for an ontology that has constituted the schema for an SQL database, the Mission Operations Directorate Enterprise Architecture Repository (MODEAR). MODEAR is in operation and is currently providing support for upcoming missions. This has enabled the formalization of the FPP and the collection and organization of the expert data which is typically used for a mission design. The process flow diagrams associated with each of the key functions within the FPP are generated and updated in Visio by the Subject Matter Experts (SMEs). These process flow diagrams are the primary means for the SMEs to convey architecture information to MODEAR. Using helper applications, MODEAR works interactively with Microsoft Visio to, one hand, provide the latest repository data to experts working on the Visio diagrams and on the other hand, conduct consistency checking on the new data created by them before uploading to the database. MODEAR facilitates the export of data associated with architectural artifacts to customized architecture development tools. Details of the FPP Re-engineering project that has created the technological framework referred to are included in [6].

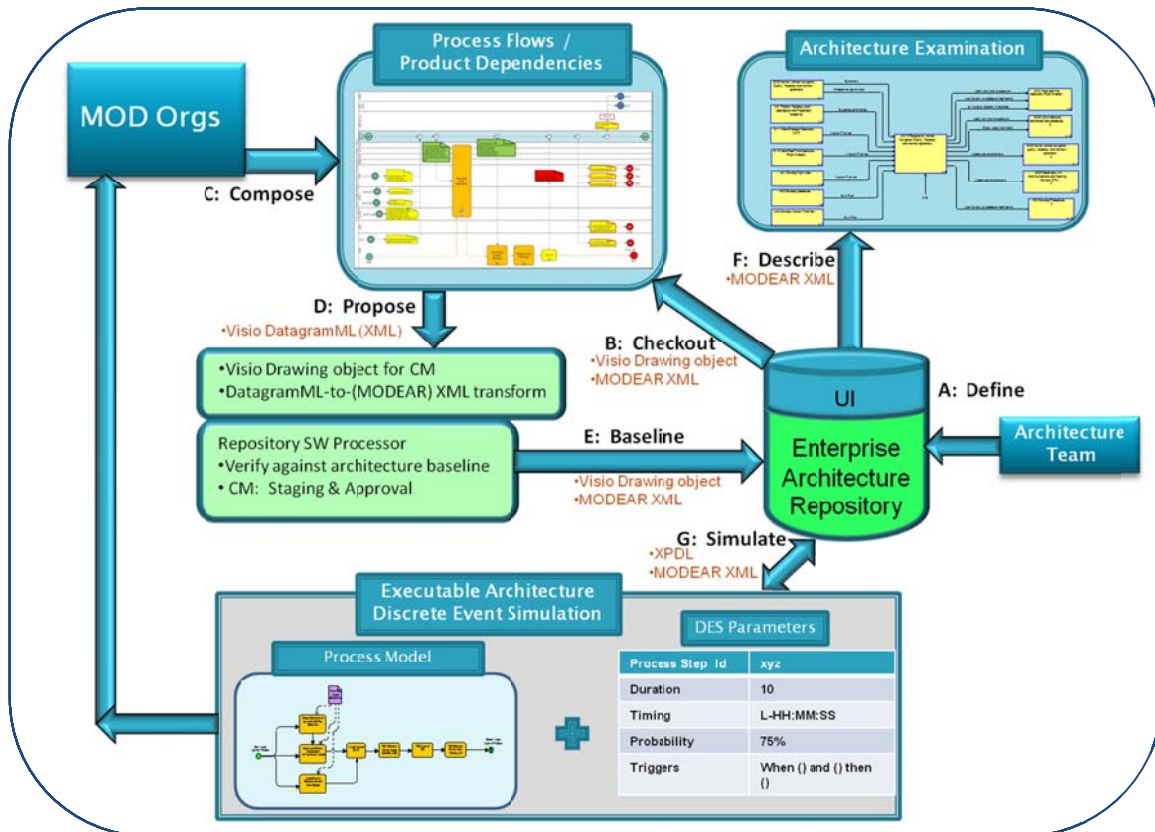


Figure 1: Process used for generating architectural and design artifacts

In the post-Constellation era, MOD is collaborating with a host of new customers. The artifacts established by the FPP Re-engineering project in support of the Constellation Program (CxP) provided a preliminary Work Breakdown Structure (WBS), data flow information and a master schedule based on the existing knowledge base in MODEAR. This knowledge base has been leveraged by refactoring the PFDs that had previously been generated for the CxP [7]. These refactored PFDs are recursively applied in the construction of what is called a Design Reference Mission (DRM). The DRM includes a general set of functions and their associated, instanced PFDs and inputs/outputs. It is meant to serve as a reference and a starting point to the development of concrete point designs for specific missions.

The current approach for designing an FPP using the existing infrastructure is for the SMEs to each sustain their associated PFDs. The data is integrated and the overarching FPP model is managed by members of the Special Analysis Team (SAT). The SAT team comprises SME members with expertise in each of the domains, Systems Engineers who conduct the integration, and architectural modeling and analysis experts. The SAT team holds a meeting periodically to review and comment on the state of the model. Based on SME coordination and discussions conducted through the SAT forum, SMEs may refine their associated PFDs. The FPP model matures through this process of SME coordination and integration.

The current process used for generating architectural and design artifacts using this framework is depicted in figure 1. The architecture team, which is also called the Special Analysis Team (SAT), first defines the general scope of the activity and PFD's that need to be customized for the study in question (A. Define). These PFDs are then checked out of MODEAR (B. Checkout) into the Visio application to be composed or refined by the SME's that represent the divisions within MOD (C. Compose). The SME's then propose changes and customizations to the PFD's (D. Propose). Their proposals are checked in to MODEAR for processing. The process includes automated consistency checking to ensure that they satisfy the baseline rules for the architecture, and depending on the sensitivity of the changes that have been made, may also include an approval cycle in which the Lead System Architect approves the changes before it is updated to the MODEAR repository (E. Baseline). Once this data has been collected into MODEAR, it is described using architectural artifacts (F. Describe) and further validated and examined using executable models such as a simulation (G. Simulation). This process is then iterated until a satisfactory design is obtained.

The vision is to extend the existing framework so that it may provide a more complete suite of tools and techniques for the purpose of supporting the decision making by Project Managers and of aiding in design optimization by System Engineers. An optimal design is one which satisfies the design criteria on schedule, while incurring minimum cost and risk. This suite would include modules for uncertainty management, decision support, and automated execution and re-planning. While each of the increments described below are in and of themselves beneficial, there are also certain dependencies between them. The second increment enhances the third increment and enables the fourth increment.

2. Second Increment: MOD System Components and the NASA Ground System

MOD at JSC is part of the NASA-wide ground systems operation; the FPP has been focused on the operations pertinent to MOD. The hardware and software which is required for pre-mission planning, training and mission execution is distributed across MOD, the agency and external entities. While the current ontology and data structure associated with MODEAR is consistent with the Department of Defense Architectural Framework (DoDAF), it includes only the workflow related to the operations viewpoint and data flow processes, as well as some level of mapping between these and the system components used for their performance. It does not currently include details about the hardware and software system components themselves. Therefore, the architectural and modeling artifacts obtained from the data in MODEAR are based on process modeling and operational view development. While this in itself has resulted in a significant re-engineering of the FPP, it does not include the re-engineering of the system components used for executing the FPP tasks. Up to this point, the efficiency obtained from this effort has been due to the elimination of the process and product redundancies in the system that has been accomplished by the formalization of these processes.

Nonetheless, visibility into the system level elements of the hardware and software system elements and interfaces that is used for performing the tasks and managing these resources further helps to enhance productivity and optimizes the system for the metrics of interest, such as cost, reliability and time to complete. Therefore the next immediate step involved in this effort is the extension of the MODEAR data model to allow for defining the system level architectural artifacts, the capture of the data associated with these elements and their connection to the tasks being performed.

The ontology that has been designed for the FPP must also interface and interact with representations associated with the rest of the MOD as well as the NASA-wide ground system. The next generation Mission Control Center (MCC) at JSC, which includes some of the hardware and software used for the generation of the flight products, and which is responsible for the generation and execution of commands to the spacecraft, currently has a variety of requirements, design documentation and system modeling associated with it. Other elements of the human spaceflight operations (including the Spacecraft System Avionics, Communications System, User Applications, etc.) each have their own associated system models as well. Therefore, there exists a distributed data structure associated with the various ground systems for spaceflight operations; and the intricate dependencies between the various elements are being designed and developed. Figure 2 is a notional depiction of some of the various pieces of a distributed ground system architecture, including the models and data repositories.

MODEAR has been designed with consideration toward a need to interface with other models and applications, and the inclusion of system level containers within its database will enable this capability. The output of the MODEAR database is defined in a standardized XML format and

is readily transformable to other tools and applications. Furthermore, data from other sources can be digested into MODEAR by conducting appropriate transformations as well.

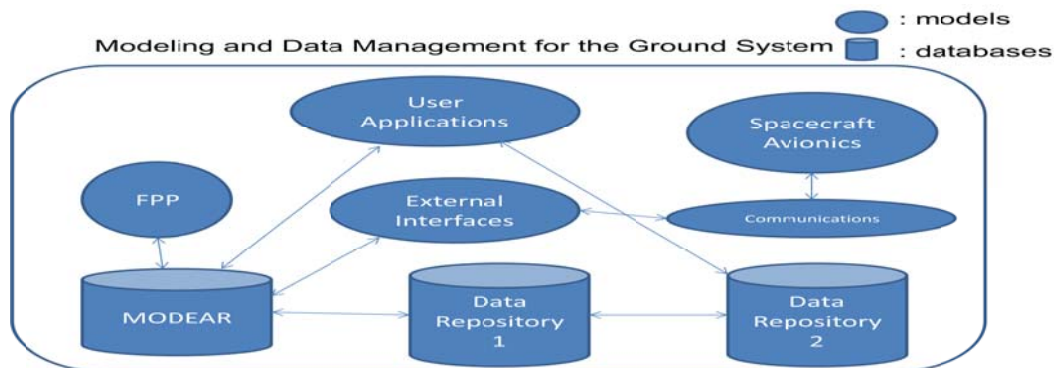


Figure 2: Modeling and data management for the Ground System

The completion of the second increment would enable the development of a more efficient FPP system altogether and the integration of the FPP with the rest of the MCC and the NASA ground system.

3. Third Increment: Uncertainty Management

The third increment provides the capability of conducting risk analysis. The use of risk-based design methodologies from early phase design is not a new concept at NASA. A good example of one such design is the Altair lunar Lander [9]. An interesting feature of this design is that it does also consider the risks associated with the human operators of the system during the design cycle and thus the systems level risk models include the hardware, software and human elements that contribute to risks.

While it is possible to simply build risk assessment models based on the workflow processes and tasks that are used to perform them, a more complete model would also include the hardware and software components of the system that are used for executing the tasks and their configuration. Therefore the third increment can even now be added to the existing background work, but in order for it to be more complete and at the system level, it needs the establishment of the second increment. Alternatively, the second and third increments could be added in parallel.

The design of the FPP is purely based on the elicitation and integration of Subject Matter Expertise (SME). The SME's considered the "best-case" scenario when estimating the man-hours necessary for performing the tasks as well as the sequences of tasks performed. This was referred to as the "happy-path". The next logical step is to identify the non-happy paths, and the things that may go wrong, or risks and develop strategies for mitigating these risks.

Broadly, the uncertainty may be due to the following reasons:

- ▶ Inaccuracies in the design

- SME's might have left out activities during the design process.
- System design without proper consideration of the operations profile and activities for the system.
- Their estimate of time and resources for the performance of activities may be inaccurate.
- ▶ Changes in requirements
 - Requirements for the mission in question may change and result in changes to the FPP process.
- ▶ Resource availability
 - Resources such as humans, hardware or software may not be 100% available. This in itself may cause a delay in the completion of associated activities.
- ▶ Errors in performing tasks

Our initial suggested approach for managing these uncertainties is to build Probabilistic Risk Assessment (PRA) models for each of the Process Flow Diagrams (PFDs) on the critical path. According to the Pareto Principal, roughly 80% of the uncertainty is due to roughly 20% of the processes [7]. The idea here is that those 20% are the processes on the critical path. Once these PRA models are built, the team will deliberate on the causes of delay or error for these PFDs. Failure data from multiple sources, such as the Human Reliability data banks from the Nuclear Industry and failure records for the various hardware and software components of the MOD FPP system are then used to populate and execute these models. Execution of these models will give insight into areas of high risk and provide guidance for margin allocation. Allocating additional margins to the sensitive areas of the system will in turn help to mitigate the risks associated with them.

For demonstration purposes, we consider a sample PFD which includes the sequence of activities: Change Request (CR) Generation, Book Manager Review & Approval, MOD Internal CR review. Figure 3 shows the Event Sequence Diagram (ESD) associated with this PFD. Note that this particular PFD represents the second set of the function “4.3.3_2: Conduct Flight Operations Reviews”. Therefore in the PRA model, it feeds into the third event tree (ET3) which represents the third step of this function. This dependency is shown via the “>>ET3” notation in the tool. For each of the activities involved, it's likely that it is conducted correctly and on time, or that there are delays or errors involved. Therefore at each event node, the tree has two branches. The upper branch indicates the success of the event and the lower branch its failure. The final tree has eight different possible outcomes since there are three events that each has two outcomes. In this case, if one activity is slightly delayed the final products are still generated correctly and on time, but if two activities are flawed there is a delay and if three are flawed, the

final outcome is erroneous products. Now each of these activities involves multiple failure modes. So in order to assess the likelihood that each of these activities will be successful or erroneous, our PRA model includes a fault tree associated with them. Figure 4 shows a fault tree associated with the activity “Book Manager Review & Approval”. As it can be seen, the book manager may omit a step involved in the process, or there may be an existing error that is not caught as he reviews the document. The likelihood of these errors is obtained from the data banks associated with human errors from the Nuclear Industry [8]. The final probability of failure associated with each of the events is indicated in the Q variable which is represented in the ESD in figure 3 as well. The probability of each of the paths occurring is indicated in the frequency column at the left.

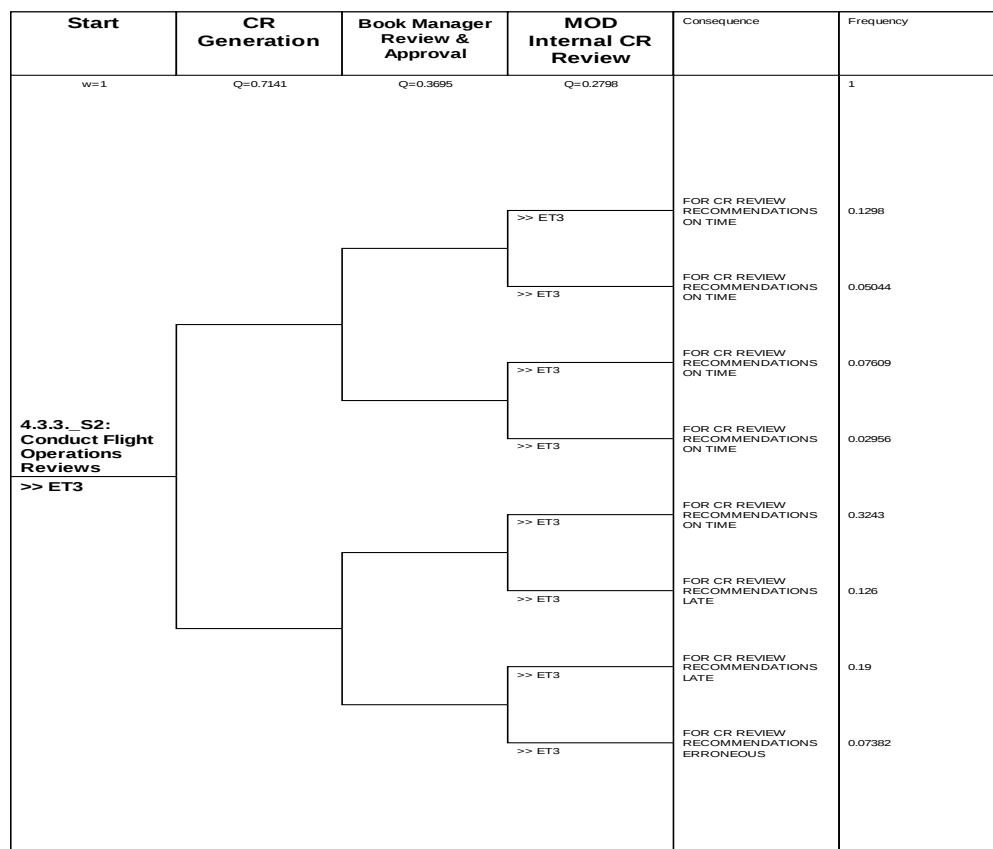


Figure 3: Sample Event Sequence Diagram for the PFD “Conduct Flight Operations Reviews”

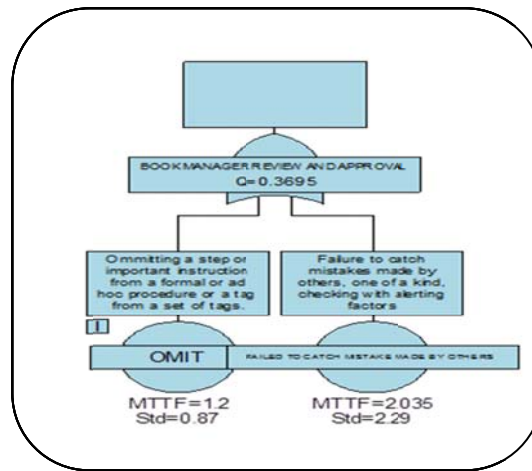


Figure 4: Sample Fault Tree associated with the event “Book Manager Review & Approval”

Another significant uncertainty involved is the estimate of the costs involved. The suggested approach for cost modeling is to map the elements of the functional breakdown for the generic FPP project into the WBS elements of projects for which there are available cost data and use that as a basis for cost estimation. While this result provides an estimate for the labor costs associated with the FPP, the facility costs can be derived by using the operational profile of the facility components that are generated from the simulation analysis.

Some of the possible outputs of the cost modeling effort include:

- An estimate for the labor costs associated with the development of the FPP for the project in question.
 - Uncertainty distribution for the estimate.
- A list of the key cost drivers for the FPP.
- An estimate for the facility costs associated with the FPP.
 - Uncertainty distribution for the estimate.

Therefore when the third increment has been completed, the iteration process with the SAT team will include brainstorming about the risks and sensitivities of the system. This information will be collected and included in a PRA model and a cost model by a modeling expert on the SAT team and the results of the PRA/Cost-risk model will be deliberated upon and iterated in order to develop optimal margin allocation strategies. The main difference is that there will be a risk and cost-risk assessment module in the loop and instead of just one baseline design, there will be several alternatives, each with a specific risk and cost profile.

4. Fourth Increment: Re-Planning and Automated Execution

The fourth increment enables the semi-automated re-planning of the initial FPP design as the actual system behavior is observed and its corresponding data collected. This increment is

dependent on the second implement and complimentary to the third increment. In other words, it is necessary to have information about the system hardware and software components within the models in order to conduct automated re-planning and execution. Furthermore, re-planning, in particular is an approach for managing uncertainties and hence complimentary to the third increment.

Risk based margin allocation was suggested as an initial approach for managing uncertainty. This is due to the fact that additional margins allocated to sensitive areas of the design provide for the resources needed for re-planning. In other words, when there are errors or inaccuracies in the design, or when the requirements change, there is a need for the team to conduct a re-plan and re-design the template accordingly. Currently, this is done in a completely manual way. In other words, the team actually has to convene, discuss the issue being addressed and form a plan for changing the design to accommodate it. Nonetheless, this re-planning process can be semi or mostly automated in time. Much of the knowledge that the SAT team uses for the re-planning process has been captured within MODEAR. Formalizing this data and representing it in a format that would be amenable to automated optimization is the first step towards automated re-planning. The next step would be the development of heuristics and use of planning algorithms for the creation of the re-planning engine.

The fourth increment calls for the development of an automated re-Planner as well as an execution engine. These two can be developed in parallel.

During the implementation of an FPP process, the tasks are triggered in order. Each task is identified by the resources required for its' processing and the prerequisites for it to begin. When the prerequisites for it have been met (i.e. all tasks on which it depends have already been processed), and the resources required for its execution are available, an automated executor or what we call an MLNE(Management Level Network Executive) triggers the application (or human expert) required to perform the task to begin processing.

The status of the task in question then goes from "idle" to "in implementation". Further, the exact time and resource that has been allocated to it will also show in its' status. When the task has completed, it will check back into the system with its final status (completed, time-stamped) and the process continues.

Throughout the implementation process, the actual measures of performance for the system are collected on a regular basis by synthesizing the data that is created from the execution of tasks. So, for instance, for each task, the time it takes to perform it and the amount of resource usage is recorded. As the system servers more and more FPP processes, a data set associated with each task is created and this data set is used to update the prior information that is collected from the SME's regarding the tasks.

Table 1 provides a list of the different types of uncertainty that could be dealt with using a Re-planning engine.

Type of Uncertainty	Type of Change Required	Approach	Level of Automation
Requirement Change	Design Change	Re-planning	Mostly automated
Delta between the design versus the actual	Resource allocation change.	Margin management, Re-planning	Mostly automated
Flight Schedule Change	Date changes	Re-planning	Mostly automated
Personnel Availability	Resource allocation change.	Re-planning	Mostly automated
Resource Availability	Resource allocation change.	Re-planning	Mostly automated
Mission Profile Change	Design Change	Re-planning	Semi-automated
Other Change Requests	Design or resource allocation changes	Re-planning or Margin Management	Semi-automated

Table 1: Uncertainty Management Techniques.

Once increment four has been completed, we have a Decision Support System that aids in the design, development, maintenance and management of the FPP. The selected baseline design will be executed semi-automatically with the commands going directly from the MLNE to the applications or humans responsible for performing the tasks. The metrics associated with the tasks will be collected and if there are discrepancies, the re-planner will develop a suggested re-plan for achieving the mission goals. The re-planner is analogous to the GPS system in a car. When it turns out that the path is different from the initially planned path, it finds an alternative path to the destination. The MLNE would then be analogous to a driver who can drive automatically for the most part but needs the actual human driver to supervise its performance and take charge as appropriate. Since the MLNE will be in communication with relevant applications, their status will also be automatically registered for the purpose of maintenance activities.

5. DSS-FPP Elements and TAMU

One of the key benefits of the approach established by the FPP Re-engineering project [6] is the fact that it facilitates MOD collaboration with other program elements and with other space agencies. This is achieved due to the systematic decomposition of the FPP and the visibility into the touch points of each of the modules or functions on which the architecture is built. The Transferable, Adaptable, Modular and Upgradeable [TAMU] features of this new paradigm are described in [5]. The Decision Support System described in the four increments above will further facilitate this collaboration by making the functions performed by the JSC based SAT team more efficient. These functions and the associated tools and approaches used for their conduct are summarized in table 2.

Function	Tool	Approach
Data Collection	Process Flow Diagrams, Visio	Visio Module - SME inputs
Integration	MODEAR	MODEAR consistency checker/ integration approach
Requirements Analysis	MODEAR ++	Transfer requirements into structured ontology and integrate with the rest of the system
Critical Path Analysis	COTS tools/ Scheduling Application	Standard CPM/ Scenario Analysis via Networks.
Architecture Development	COTS tool	DODAF
Optimization	Planner/ To be developed	AI Planning Algorithms
Synthesis	SAT Team	Team Consensus/ Discussions
Uncertainty Management	Re-Planner/ To be developed Isograph Reliability Workbench	AI Planning Algorithms Probabilistic Risk Assessment
Execution	MLNE (COTS tool) / To be developed	Automated Execution

Table 2: Key Functions performed by the FPP and their corresponding tool and approaches.

6. Summary & Conclusions

This paper explains the steps involved in extending a newly developed technological infrastructure into a full-on Decision Support System to support the development of Flight Products in a semi-automatic and optimal manner. The vision for this development reflects a developmental framework for MODEAR and the FPP model, which is divided into four increments, where the first increment has already been accomplished and is operational. It is important to point out that this first increment is already providing much added value and the expectation is for each of the remaining increments to have significant value and return on investment in and of themselves. Nonetheless, the way they have been designed, there is some level of dependency between these increments and each builds on the previous ones quite productively.

7. Acknowledgements

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